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A GEOPAUSE SATELLITE SYSTEM CONCEPT

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ABSTRACT

The forthcoming 10 cm range tracking accuracy capability holds much promise in connection with a number of earth and ocean dynamics investigations. These include a set of earthquake-related studies of fault motions and the earth's tidal, polar and rotational motions, as well as studies of the gravity field and the sea surface topography which should furnish basic information about mass and heat flow in the oceans.

The state of the orbit analysis art is presently at about the 10 meter level, or about two orders of magnitude away from the 10 cm range accuracy capability expected in the next couple of years or so. The realization of a 10 cm orbit analysis capability awaits the solution of four kinds of problems, namely, those involving orbit determination and the lack of sufficient knowledge of tracking system biases, the gravity field, and tracking station locations.

The Geopause satellite system concept offers promising approaches in connection with all of these areas. A typical Geopause satellite orbit has a 14 hour period, a mean height of about 4.6 earth radii, and is nearly circular, polar, and normal to the ecliptic. At this height only a relatively few gravity terms have uncertainties corresponding to orbital perturbations above the decimeter level. The orbit is, in this sense, at the geopotential boundary, i.e., the geopause. The few remaining environmental quantities which may be significant can be determined by means of orbit analyses and accelerometers. The Geopause satellite system also provides the tracking geometery and coverage needed for determining the orbit, the tracking system biases and the station locations. Studies indicate that the Geopause satellite, tracked with a 2 cm ranging system from nine NASA affiliated sites, can yield decimeter station location accuracies. Five or more fundamental stations well distributed in longitude can view Geopause over the North Pole. This means not only that redundant data are available for determining tracking system biases, but also that both components of the polar motion can be observed frequently. When tracking Geopause, the NASA

sites become a two-hemisphere configuration which is ideal for a number of earth physics applications such as the observation of the polar motion with a time resolution of a fraction of a day.

Geopause also provides the basic capability for satellite-to-satellite tracking of drag-free satellites for mapping the gravity field and altimeter satellites for surveying the sea surface topography. Geopause tracking a coplanar, drag-free satellite for two months to 0.03 mm per second accuracy can yield the geoid over the entire earth to decimeter accuracy with 2.5° spatial resolution. Two Geopause satellites tracking a coplanar altimeter satellite can then yield ocean surface heights above the geoid with 7° spatial resolution every two weeks. These data will furnish basic boundary condition information about mass and heat flows in the oceans which are important in shaping weather and climate.

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I. INTRODUCTION

The prospect of developing laser and electronic ranging systems and VLBI instrumentation capable of decimeter accuracy opens up the possibility of conducting a number of earth physics and oceanographic investigations which are expected to be scientifically important and of practical value from the applications standpoint as well. Phenomena associated with the earth's dynamical and crustal motions and its sea surfaces are all of interest in connection with the emerging programs which are intended to exploit these new scientific and applications capabilities.

The present state of the art is one or two orders of magnitude away from the projected instrumental accuracy levels. This is due largely to limitations in our knowledge of the earth's gravitational field and figure, and the need for the solution of problems involving orbit determination and tracking system biases. (Cf. references 1-23.)

The purpose of this discussion is to indicate ways in which the Geopause spacecraft system concept can contribute to the achievement of the earth physics and oceanographic goals which the instrumentation technology appears to have placed nearly within our grasp.

The scientific and applications aspects of the program are described in more detail in reports of the National Academy of Sciences and NASA. (24-26)

Portions of these documents which are of special interest here are briefly reviewed in the following discussion.

In the area of earth dynamics there is interest in observing tectonic plate motions of more than one type. The gross motions of the tectonic plates with respect to one another, such as the continental drifts, are important for the understanding of the continuing evolution of the earth's crustal surface. Fault zone regions of the type which are found at the interfaces between two tectonic plates are of special interest in connection with earthquakes. More detailed information about the deformations of the tectonic plates in the neighborhood of a fault zone can be used to estimate the amount of energy stored in the region. Such data may one day form the basis for earthquake risk predictions.

The study of these types of tectonic plate motions calls for observational capability in the decimeter range, since the annual motions involved are estimated to be of the order of a few centimeters to somewhat over a decimeter.

Evidence for correlations between earthquakes and anomalies of the polar motion has been found by Smylie and Mansinha (27). These studies are currently limited by the fact that polar motions are normally observed in terms of five day means with accuracies of the order of a meter or so. The ability to observe polar motions with decimeter accuracy over time intervals of the order of a day or less would clearly be of real value here.

The capability for observing crustal motions at the decimeter level carries with it the ability to observe solid earth tides. Amplitudes of the solid earth tides are of the order of a third of a meter. They may vary from place to place on a tectonic plate. The nature of any correlations which may exist between tidal processes and earthquakes has been a subject of investigation and discussion for some time. Additional observational data may shed light on this important question. Observations of tidal motions at points near fault zones may be of special interest in this connection, for example. These could be made in conjunction with the fault zone plate deformation measurement program indicated above.

These studies all involve the observation either of the relative motions of points on the earth's surface, or of the dynamical motions of earth as a whole, with uncertainties on the order of a decimeter.

Satellite altimeters capable of decimeter accuracy are expected to open up the possibility of observing many phenomena of great interest to oceanographers. For example, knowledge of the height of the ocean surface relative to the geoid with decimeter accuracy will make possible studies of a number of phenomena including the general circulation of the ocean and deep ocean tides. Current models of the general circulation of the ocean are based upon the assumption that there exists a level of no motion at a depth of one or two kilometers. Measurements of the height of the mean sea level surface relative to the geoid to decimeter accuracy will provide basic boundary condition information which will minimize the need for such a restrictive assumption.

Some oceanographic studies, involving the local details of currents and storm surges, for example, can be carried on profitably to a certain extent without a comprehensive reference system. Studies of such topics, too, would, however, be expected to benefit from the use of the kind of decimeter capability needed to tackle the problem of the general circulation of the oceans.

In order to transform satellite altimeter measures of decimeter accuracy to correspondingly accurate knowledge of the ocean surface height above the geoid, it is necessary to know the height of the satellite altimeter itself relative to the geoid with comparable accuracy. One way to obtain this knowledge is to find the position of the satellite altimeter with reference to the earth's center, and to map the geoid in the same reference system to similar accuracy. Here again one faces the problem of determining position, this time of the altimeter satellite, with decimeter accuracy relative to a reference system associated with the earth's center. Mapping the gravity field and the geoid can be accomplished through satellite-to-satellite tracking between a high-altitude satellite and a low-altitude, drag-free satellite, which is often referred to as an earth harmonic or gravity field satellite.

The magnetic field can be charted by means of a similar kind of low-altitude magnetic field satellite and, again, tracking from a high-altitude satellite is important since it provides data for the determination of the orbit to the required accuracy.

Information about both the gravity and magnetic anomalies can, in turn, be studied to learn more about the earth's crustal structure, evolution and dynamics.

The various earth and ocean physics studies outlined here will be of value in connection with a number of scientific disciplines. In addition, applications benefits in several areas will be looked for in time as is indicated in Figure 1.

The following discussion deals with the Geopause spacecraft system concept and its potential use together with gravity and magnetic spacecraft to map the earth's gravitational and magnetic fields, its potential use together with the altimeter spacecraft to monitor the ocean surface, and its potential use directly for charting the locations and motions of points on the earth's surface which, in turn, will make possible the determination of the polar motion, UT 1, continental drift, and fault motions. Other approaches including VLBI, laser ranging to the moon and to other earth satellites, and gravity gradient gradiometers offer promise in connection with one or more of these programs. From many standpoints these various approaches can be regarded as being potentially complementary. This discussion will concentrate upon the potential of the Geopause spacecraft system concept. Possible relationships to other programs will be indicated at times.

II. THE GEOPAUSE SATELLITE SYSTEM

A. Potential Contributions of the Geopause Satellite System

The discussion of the Geopause spacecraft system concept will begin with a brief sketch of the system and some of its expected capabilities.

The Geopause satellite system is conceived of as offering promising approaches to the solution of the four kinds of problems which stand in the way of the advance from a ten-meter state of the art to a decimeter capability.

These are the problems associated with orbit determination and inadequate knowledge of station positions and motions, tracking system biases, and the environment including, in particular, the earth's gravity field.

The Geopause orbit is at a distance of about four or five earth radii and is nearly circular, polar and normal to the ecliptic, i.e., the right ascension of its ascending node is ninety degrees, say. The following discussion will deal with the case of the Geopause orbit having a fourteen-hour period. Orbits having other periods in the neighborhoods of 10, 19, and 31 hours, for example, possess similar properties.

Uncertainties in geopotential harmonic coefficients give rise to corresponding uncertainties in the components of the satellite position. For a satellite at an altitude of about 4.6 earth radii, uncertainties of only a very few geopotential coefficients correspond to significant position perturbation uncertainties above the decimeter level. Such an orbit can be thought of as being, in this sense, at the boundary of the geopotential i.e., at the "geopause".

Effects associated with other forces have uncertainties which are negligibly small, or which can be observed or evaluated with sufficient accuracy in this context. This point is discussed further later.

The good geometrical coverage provided by the Geopause orbit makes it possible to pinpoint station positions. A proposed set of some ten well-distributed NASA affiliated sites whose positions are accurately determined by means of Geopause spacecraft tracking can serve as a network which is a fundamental one in this sense.

The Geopause satellite can be observed almost continuously from such a fundamental network. Often four or more fundamental stations view Geopause simultaneously, hence it becomes practical to evaluate biases in the range tracking systems on a continuing basis.

When Geopause is over the pole, it can actually be observed by all stations having latitudes greater than about 30°, hence it is ideal for monitoring polar motion. Similar remarks apply to its good capability for monitoring variations in the earth's rotational rate. The ability to determine station positions with decimeter accuracy carries with it the ability to monitor and observe continental drift and the deformation of tectonic plates in the neighborhood of fault zones with comparable accuracy. It has been estimated that range rate tracking at the 0.03 mm per second level from a Geopause spacecraft to a coplanar drag-free, gravity field spacecraft in the 250 to 300 km altitude region can provide the basic data for determining the gravity field and the geoid over the entire earth to decimeter accuracy.(

Range tracking from two Geopause spacecraft in the same orbit but separated in mean anomaly by about a quarter of a revolution can provide the basis for accurate determination of the position of coplanar altimeter spacecraft with respect to the earth's center and the geoid.

This information, together with satellite altimeter data of comparable accuracy, can lead to the determination of the ocean surface height relative to the geoid. Data of this type are of fundamental importance to such oceanographic investigations as the study of the general circulation of the oceans.

Tidal data should be derivable in two ways. It will be derivable in the first instance through direct analysis of the data obtained by tracking the Geopause spacecraft from the network of fundamental stations. The greatly improved knowledge of the locations of the fundamental stations will, in turn, make it possible to obtain correspondingly improved knowledge of the positions of a number of other satellites of geodetic and geophysical interest including, for example, synchronous satellites. The effectiveness of the nearly geostationary satellites as tidal monitors will be enhanced considerably as a result of the improved knowledge of their positions and velocities which can be derived on the basis of Geopause results.

B. Geopause Satellite System Characteristics

1. Orbit Determination Considerations

It is helpful in analyzing certain properties of the Geopause orbit to look at the Geopause observational geometry. The Geopause satellite is observed from the earth in directions which are always within about $1/a$ radians of the nadir line, where the semi-major axis, a, is expressed in earth radii. Range observations of the Geopause spacecraft having an uncertainty of $\delta\rho$, say, provide the basis for determining radial and horizontal components of the Geopause position with uncertainties which are approximately proportional, respectively, to

$$\sec\left(\text{arc sin}\,\frac{1}{a}\right)\delta\rho \quad , \text{ and } \quad a\,\delta\rho \quad ,$$

where the former expression is within about two or three percent of unity in the Geopause case. (Cf. Figure 7.)

Thus in estimating the effects of uncertainties in various perturbations, we find that the radial perturbation uncertainty has what is essentially a direct effect upon the accuracy while the horizontal perturbations have an effect which can be thought of as being diminished by approximately the factor $1/a$.

It is convenient for certain purposes, therefore, to think in terms of an effective horizontal perturbation uncertainty amplitude which is smaller than the horizontal perturbation uncertainty amplitude by the factor 1/a.

2. Environmental Factors

a. The Gravitational Field of the Earth

Estimation of the uncertainties in the Geopause positions due to corresponding uncertainties in the harmonic coefficients of the earth's gravitational field involves an estimate of these latter quantities. Formal standard deviations of the coefficients for each of the lower degrees of the SAO 69 (II) field appear in Table III (28). Quantities of this type may tend, at times, to represent underestimates of the uncertainties since they do not always reflect all the significant sources of error. Accordingly, differences between coefficients in several of the recent models listed in Table I were also looked at. For example, mean values of the differences between coefficients of two of the SAO models were obtained for each degree. In addition, a mean doppler field was determined by averaging the coefficients obtained in the NWL 5 E-6 and the APL 3.5 models of Table I. The differences between the coefficients of this mean doppler field and the SAO M-1 optical field, which was of a similar vintage, were averaged again for each degree. Results obtained in this way are listed in Table III.

The coefficients in a given solution are determined as a set and tend to be rather highly correlated. The difference quantities of Table III, if taken to represent uncorrelated values, may thus tend to lead to over-estimates of errors in some cases. This may not necessarily be so for cases which are not well represented, in terms of orbital inclinations and eccentricities for example, in the gravity solutions considered in the table. The halves of the differences, $\Delta \ell_{1,2}$, between the degree means for the optical and mean doppler fields are sometimes viewed as providing rough indications of the corresponding probable errors associated with these fields. Their average value is about 6×10^{-8}. They reflect the state of the art of about five years ago. The SAO M-1 and 69 (II) fields are considered to be roughly comparable to each other in accuracy to degree and order eight. It is not surprising, therefore, that the differences $\Delta \ell_{1,2}$ and $\Delta \ell_{2,3}$ between these two fields and the mean doppler field are also generally comparable, and somewhat larger than the differences $\Delta \ell_{1,3}$ between the two SAO fields. The means of the halves of the latter two sets of differences, $\Delta \ell_{2,3}$ and $\Delta \ell_{1,3}$, are about 5 and 3 parts in 10^8, respectively. The current state of the art is probably somewhat better than that indicated by the differences $\Delta \ell_{1,2}$ or $\Delta \ell_{2,3}$ between the two SAO fields and the mean doppler field of some five years ago. On the basis of considerations such as these, the uncertainties in the normalized values for the gravitational harmonic coefficients are taken to be the following ones:

$$2.5 \times 10^{-8}, \text{ for } \ell = 2, \text{ and}$$
$$5 \times 10^{-8}, \text{ for } \ell > 2. \qquad (1)$$

Amplitudes of perturbation components in the radial, along-track and cross-track directions were calculated on the basis of Kaula's theory. (29) The perturbation amplitudes were calculated by using the values given above in the expressions (1) for the harmonic coefficient uncertainties.

The results of such calculations can be presented or summarized in various ways.

Gaposchkin employed sensitivity coefficients in discussing the gravitational perturbations of certain satellite orbits. (28) Each such coefficient is associated with a given degree and order. It actually represents the effects of all of the terms of that degree and order for all the values of p and q which are significant at a given level. Some notion of the utility of sensitivity coefficients for orbits of the GEOS type can be gained by simply noting the number of individual terms involved. For example, one can take the value of 0.05×10^{-6} for the uncertainty for all values of l and evaluate the terms for which along-track perturbation amplitudes greater than 5 cm occur. Doing this one comes up with well over a thousand individual non-resonant terms for GEOS-I. In the case of the Geopause satellite orbit, however, the gravitational perturbations are so small that only seven such terms occur, hence it becomes practical to think directly in terms of the individual significant terms corresponding to specific sets of values for the indices l, m, p, and q. Another simple index is the root sum square of all non-resonant perturbation amplitudes. For the case just discussed, this turns out to be about twenty meters for GEOS-I, and less than a meter for the Geopause spacecraft. The GEOS value is reasonably consistent with the kinds of uncertainties obtained by comparing different

gravity models in terms of corresponding differences in spacecraft positions as can be seen from Table IV. (Cf. references 30 & 31).
This thus gives an additional indication of the reasonableness of the assumptions concerning the uncertainties in the gravitational harmonic coefficients.

Employing the uncertainties specified above in (1), one finds the terms having corresponding along-track perturbation uncertainties more than five cm. Of these, the ones for which the radial or effective horizontal perturbation uncertainties are more than five centimeters are the five listed in Table V.

It is proposed to solve for the harmonic coefficients listed there, as well as for GM. Similar thoughts apply in the case where one aims at somewhat greater accuracy.

b. Luni-Solar Perturbations

Secular perturbations of the node vanish for the 90 degree inclination of the Geopause orbit. Luni-solar perturbations of the Geopause orbit are minimized over long periods by choosing the orbit plane to be normal to the ecliptic. Perturbations to the inclination and the node are small, being no more than about a tenth of a degree for half a decade or more.
The perturbations can be made still smaller for a specific time interval, such as the anticipated active life time of a particular Geopause spacecraft, say, by choosing an orbit plane which will have this property. It will be normal to a plane which represents a weighted mean position in an appropriate sense for the lunar and solar orbit planes during the interval of interest. Over intervals as long as about nineteen years the mean ecliptic would serve as such a plane for practical purposes.

c. Non-conservative Forces

Effects of non-gravitational forces, such as those associated with radiation pressure, drag and micrometeorites, can be evaluated by means of accelerometers. It is anticipated that only the radiation pressure effects will be really significant here. Short period solar radiation pressure perturbations have amplitudes of the order of ten meters for a spacecraft in a Geopause orbit having an areal density of the order of ten grams per square centimeter. Accelerometer capabilities in the neighborhood of the 10^{-11} to 10^{-12} g range should give adequate accuracy.

Radiation pressure effects might also be gotten at in another way. It appears, for example, that it may be feasible to observe the solar flux with accuracies which are in the range from 0.01 to 0.04 %. The corresponding orbital uncertainties are of the order of less than a centimeter. Effects of radiation from the earth can be accounted for in similar fashion. Relatively simple monitors in the visible and infrared region should suffice to supply the necessary accuracy.

Annual variations of the reflectivity of solar cell surfaces in orbit due to the space environment have been found to be on the order of 40% in the 3000Å to 4000Å region, and 10% over the entire visible region above 3000Å. Thus, a variation rate of the order of one part in 5000 per revolution can be expected. The secular component of this variation can be observed through its cumulative effect on the orbit by solving for the appropriate parameters in the differential correction procedure. Variations from such an average rate will probably have a negligible effect. These, too, might be monitored, however.

3. Fundamental Station Locations

The complete solution of the orbit determination problem to a given level of accuracy involves not only the force model effects but also the determination to comparable accuracies of the locations of reference positions on the earth's surface.

The classical fundamental problem in determining the locations and motions of a spacecraft such as the Geopause satellite is thus bound up with that of determining the positions and motions of a set of reference tracking stations on the earth's surface. A system of Geopause spacecraft may one day serve as an independent reference system. For the moment, however, one can consider the problem of determining the positions and motions of the components of a system consisting of the Geopause satellite and a set of fundamental tracking sites. One can begin with the eight sites in the Goddard network which are shown in Figure 2. Kashima and Naini Tal, which have been affiliated with NASA, are also valuable locations which are indicated in the figure and discussed further below.

Range and range rate tracking equipment of the GRARR, USB or ATS types are or have been located at each of the Goddard sites.

The accuracy capability of this equipment is currently much less than that required for the earth physics program, e.g. 2 to 10 cm. in range and 0.1 to 0.03 mm per second in range rate with a 10-second integration time. Nevertheless these stations provide a good place to begin thinking about future capabilities.

These locations are also equipped with parabolic dish antennas having diameters of 40 and 85 ft. Three of them will also feature 210 ft. diameter deep space network antennas. These facilities can make possible the conducting of VLBI measurement programs using natural radio sources as well as artificial sources such as the Geopause spacecraft itself. The use of synchronous satellites in this fashion is already under way.

These fundamental locations are also the ideal ones from which to make laser ranging observations of the Geopause satellite. This will permit the determination of the locations and motions of these fundamental sites by means of all three of the techniques which offer promise of decimeter accuracy, i.e., lasers, electronic ranging systems, and VLBI.

An obvious geometric gap in the Northwest Pacific area exists in this network. It is proposed to fill it by adding the Kashima site to the network. The Kashima station has participated extensively in the NASA, GSFC ATS program. Similarly Naini Tal, which was a NASA tracking site for many years, is in a good position to strengthen the polar motion and UT1 coverage.

The problem of determining the locations and motions of the Geopause spacecraft from the fundamental ground stations can be viewed in terms of the tracking geometry considerations which were discussed above. It was pointed out there that the range observations of the Geopause spacecraft provide the basis for determining its radial position with an accuracy which is not diminished significantly by geometrical factors. Similarly range observations of the Geopause spacecraft provide the basis for determining a station position component in the direction making an angle θ with the observing line with an uncertainty which is proportional to sec θ. (Cf. Figure 1 .)

This again reduces to unity to within about three percent for values of θ less than a quarter of a radian. Observations of a Geopause satellite in three mutually orthogonal directions at elevation angles above about 15° provide the basis for locating the station without significant geometrical dilution of the instrumental range accuracy. The mutually orthogonal triad of directions at an elevation angle of about 35° with azimuths separated by 120° which is illustrated in Figure 1 , is an example of such a set of directions.

The Geopause satellite orbit provides the kind of tracking geometry which furnishes an abundance of these mutually orthogonal triads in the zone of good observing which lies roughly between the elevation angles of 15 degrees and 70 degrees. This is indicated in Figure 2 where the ground tracks of Geopause for a week are shown. The corresponding triad for a possible station at Quito is also shown. It is clear that the Geopause satellite orbit generously provides the kind of geometrical coverage needed to pinpoint the locations of the fundamental tracking stations.

Further indication of this is obtained from the results of an analysis involving simulations of the tracking of Geopause from such a network. The observations were made at each station at intervals of fifteen minutes when the Geopause was above an elevation angle of 15 degrees. Bias values of 10 and 2 centimeters were assumed there for the range observations. Variations in the gravitational harmonic coefficients were taken to be 25% of the difference between the values given in the SAO MI and APL 3.5 models, i.e. the second and third models of Table I. These uncertainties were also found to correspond well with uncertainties experienced with tracking data (cf. reference 32).

A priori estimates of uncertainties in tracking station locations were taken to be 10 meters. A system such as this yields relative longitudes, hence, the longitude coordinate of one of the stations is tightly constrained. It was convenient to do this for a simulated station, denoted "Rosman prime", which was chosen to have a longitude of 90 degrees west and a latitude and height equivalent to that of the basic Rosman station. Its coordinate in the longitude direction was assumed to have an a priori uncertainty of a millimeter. Assuming 10 centimeter tracking system biases and solving for the Geopause orbit elements, the locations of all of the tracking stations, GM and the

(2,2) term, the results indicated in Table VI were found. The rms value of the station location uncertainties found in this solution was about twenty-eight centimeters.

In order to arrive at a system which could more effectively exploit the two centimeter range data which is expected from laser and/or electronic ranging systems in the future, several lines of attack were followed. The (4,2), (4,3), and (4,4) terms should have perturbation uncertainty amplitudes of about four centimeters, given the assumptions which are indicated above. Accordingly, a solution was obtained in which, in addition to the harmonic coefficients appearing in Table V, the (3,1), (4,2), (4,3), and (4,4) terms were also solved for. The geometry of the network of fundamental stations was strenthened through the addition of a station at Comodoro Rivadavia, Argentina, where a NASA Baker-Nunn camera has been located. Using the two centimeter range bias figure indicated above, it was found that the station coordinate uncertainties had a maximum value of about five centimeters and an rms value of about three centimeters. The uncertainties in the radial components of the position of the Geopause spacecraft had a maximum value of about a decimeter and an rms value of about three centimeters. Such simulation results should be viewed with due caution, since all significant effects may not be appropriately represented. They do, however, provide helpful indications of possibilities.

It is planned to conduct further studies, e.g., taking into account in calculations such as these the contributions to the uncertainties which are associated with radiation pressure, luni-solar perturbations, different models for geopotential uncertainties and tracking system biases, etc.

4. Tracking System Biases

The Geopause satellite is visible simultaneously from four or more stations at various parts of its orbit. This can be seen from Figure 2, for example. Thus one sees that a convenient, ready means for continually observing and evaluating tracking system biases is supplied by the Geopause satellite orbit. This is a point of fundamental importance. Up to now tracking systems used for satellite geodesy have been calibrated ultimately by means of the star catalogues provided as a result of centuries of painstaking effort devoted to the problem by astronomers. Thus the biases have been removed in this way from the optical tracking systems to roughly the 10 meter level for typical geodetic satellite orbits. As the science of satellite tracking moves toward greater accuracies, it will become important to determine effective ways to eliminate the unwanted effects of tracking system biases. Submeter data have already been obtained. Decimeter accuracies are projected for the relatively near future, and two-centimeter accuracies stand as a goal for the tracking systems of the 70's. The Geopause satellite, however, provides a practical means for solving the tracking system bias problem on a continuing basis. It is essential that this tracking instrument bias problem be addressed successfully if the dramatic accuracy possibilities of the new systems are to be fully realized.

III. SCIENCE AND APPLICATIONS

A. Geodynamics

1. Fault Motions and Continental Drift

The Geopause satellite orbit system, as was pointed out in the preceding discussion, offers the prospect of the capability for determining the location of a set of stations in a fundamental network with decimeter accuracy in a relatively short period, e.g., in a matter of weeks or perhaps even a week or so. This capability provides the basis for observing tectonic plate motions whose time constants are long relative to a few weeks. These include continental drift and plate deformations in the neighborhoods of fault zones.

2. Polar Motion and UT 1

The Geopause satellite system also furnishes ideal geometry for monitoring polar motion. This is indicated in Figure 2, for example. When the Geopause spacecraft is over either pole, it is readily visible at reasonable elevation angles, i.e., in the neighborhood of 15 - 35 degrees, from a number of fundamental stations in both hemispheres. This elevation angle is thus large enough, i.e., over about 15 degrees, to avoid serious refraction uncertainties. At the same time it is small enough in the sense of the discussion associated with Figure 1, i.e., less than half a radian or so, to provide good geometry for observing the desired variations. It is seen that the fundamental network includes sets of stations in both hemispheres which are separated by roughly 90 degrees of longitude. Thus it is possible to monitor two nearly orthogonal components of the polar motion when the Geopause satellite is near the pole. This occurs about each seven hours. In fact, the Geopause spends over an hour within 15 degrees of each pole during its orbital motion, hence both components of the polar motion can be observed under reasonably good geometrical circumstances at times separated by about a quarter of a day or less.

The in-plane component can be observed more frequently. In general, this can be done anytime Geopause appears at some station at an elevation angle which is reasonable in the sense just discussed, i.e., in the 15 - 35 degree range.

The variation in the earth's rotational rate can be monitored whenever the Geopause is near the equator, e.g., within about 15 degrees of it, say.

This also occurs at intervals which are separated by about a quarter of a day. The Geopause is thus well suited for monitoring the fine structures in the polar motion and UT 1.

3. The Inertial Reference System

The orbit of the Geopause can be referred to the inertial coordinate reference system through very long baseline interferometry (VLBI) observations of radio stars at stations of the fundamental network. This could be done at those intervals which would be of interest in connection with this problem, i.e., at intervals which would be expected to shed light on any uncertainties in the motion of the Geopause satellite, or on effects which would be of special interest. In general, it is anticipated that the Geopause satellite system would be ideal for monitoring such things as polar motion and UT 1 relatively conveniently in periods between the comparisons with the VLBI determinations.

4. Earth Tides

The Geopause system will also be useful for observing solid earth tides. The orbit is nearly fixed in inertial space, hence in any given relatively short time period, such as a third of a week, say, it sees regions of the earth which are all within about an hour of the same tidal phase. In such a time interval the Geopause will have crossed the equator eight times, the largest interval between these equator crossings being only sixty degrees. Thus the entire earth is sampled in a representative way for each portion of the lunar tidal cycle.

Similar remarks apply to the sampling of the solar tidal components except that here, the observation interval is half a year and the detail obtained is correspondingly greater. The Geopause satellite can thus provide the basic data sets for a global survey of solid earth tides.

In addition, the greatly increased knowledge of the locations of the ground tracking stations which Geopause will provide will make it possible to obtain much more accurate orbits for other satellites such as the geosynchronous ones, for example. This will enhance correspondingly the effectiveness of geosynchronous satellites as spacecraft which can monitor the fine structure of the tidal motions throughout the semi-diurnal cycles for different declinations of the moon and the sun.

B. Global Surveys

1. Gravity Field Surveys

The Geopause satellite is also an ideal object from which to conduct satellite-to-satellite tracking of low altitude satellites which are used to sense the geopotential and the magnetic field and to conduct altimeter surveys of the sea surfaces. Geometry well-suited to these problems is obtained by placing the low altitude satellite in the Geopause orbit plane. We can look, for example, at the problem of sensing fine structure of the earth's gravitational field by observing perturbations in the orbit of a satellite orbiting in the 250 - 350 kilometer altitude range. As the low-altitude satellite orbits below Geopause, range-rate tracking between the two spacecraft gives the radial component of the lower altitude satellite's relative velocity when the latter is directly below the Geopause. It gives the along-track component when the low-altitude spacecraft is in the portions of its orbit which are nearly a quarter of a revolution from the sub-Geopause point. The geometry is indicated in Figure 3 , in which the view of the Geopause orbit plane is depicted from a point which is at some distance outside of it. The sub-satellite tracks of both the low-altitude satellite and the Geopause satellite during such a passage of the former beneath the latter are shown in Figure 4. On the next revolution of the low-altitude satellite this pattern is shifted by some 23 degrees of longitude and about 44 degrees of latitude. If the orbit of the low-altitude gravity field satellite is chosen so that it completes 15-9/10 of its nodal periods in one sidereal day, its ground track will repeat in ten days and will include 159 equally spaced ascending equator crossings separated by about 2-1/2°. Such a ten-day period will be referred to as a ground track interval. An orbit of this type provides the kind of geometrical coverage needed for sampling the earth's gravitational field from this altitude.

In this time period, some 142 regions of the low-altitude spacecraft's orbital path, roughly one each 1.1 revolutions, will have been observed through tracking from the Geopause spacecraft. The remaining coverage regions of the set of 142 occur in an analagous progression. Each one is displaced along the low-altitude spacecraft orbit from the previous one by about 1.1 revolutions, which means, for example, that initially its ground track is displaced to the West in longitude by about 23 degrees, and ahead in the orbit by about 44 degrees. The coverage of earth's gravitational field by the low-altitude spacecraft during periods when it is being tracked by the Geopause thus includes portions, of this type, of the set of low-altitude spacecraft ground tracks which cover the entire earth with spacings at equal intervals. at the equator of about 2-1/2 degrees.

The period of the Geopause satellite can be chosen so that it completes 67^{o} more than 17 nodal revolutions while the low-altitude satellite completes 67^{o} more than 159 nodal revolutions in about ten days and 17 minutes. Thus, as the Earth Harmonic spacecraft moves along the same track which it covered during the first revolution it passes under the Geopause spacecraft again, but this time at a point which is more advanced in its orbital path by about 67 degrees. Some seventeen minutes earlier, after exactly ten sidereal days, the low-altitude spacecraft had completed just 159 revolutions and the Geopause spacecraft had travelled about 60^{o} more than just 17 revolutions. This means that the portion of the first revolution in which the radial velocity component was observed, when the low-altitude gravity field spacecraft was directly under the Geopause, i.e. at the point at latitude 0, longitude 0 in Figure 4, becomes the portion of the 160th revolution of the low-altitude gravity field spacecraft in which a significant along-track component is observed, since the Geopause spacecraft is now more advanced in its orbit by some 60 degrees. The elevation angle of the Geopause satellite as seen from the low altitude gravity field spacecraft is then about 18^{o}. This is low enough to permit observation of a significant component of the along-track velocity, i.e., about ninety-five percent of it, and yet high enough to avoid long paths through the ionosphere's F2 layer near its maximum density, the path being only about three times that for vertical incidence.

The symmetrical configuration occurs some 17 minutes later in each of these revolutions, i.e., the 1st and the 160th. The Geopause observes the radial velocity component in the 160th revolution and a component nearly along the track in the 1st revolution. The Geopause thus observes two nearly orthogonal components of the velocity of the low altitude gravity field spacecraft as the latter traverses the same track in these two seventeen minute intervals which span 67° in the first and the 160th revolutions of the low-altitude satellite, i.e., at the beginning of the first and second ground track coverage intervals. The passage over this track in the first revolution is indicated in Figure 4. In similar fashion, in the 2nd and 161st revolutions, the Geopause observes two nearly orthogonal components of the velocity of the low-altitude gravity field spacecraft as the latter traverses the same track in an arc about 67° long which is displaced by some 23° in longitude and 44° in latitude from the corresponding arc covered in the first and 160th revolutions. A similar arc about 67° long is covered in the third and 162nd revolutions, etc., until, at the end of the second ground track coverage interval, some 143 such arcs have been covered in this same, two-component sense. The process repeats. Coverage of a second set of 143 such 67° arcs, each one adjacent to its counterpart in the first set, is completed in the same two-component sense in the third ten-day ground track interval, etc. Coverage of the six sets of 143 arcs, each 67° long, is completed in six ground track sampling intervals, or sixty days.

As was indicated earlier, the elevation angle of Geopause as seen from the low altitude satellite becomes as small as about 18°, the path through the ionosphere being some three times longer than the vertical one. This relatively short path length helps to lessen the effect of possible time variations in the ionosphere during the range rate integration interval which typically would be about 10 to 30 seconds long. Horizontal ionospheric gradients could decrease the effective elevation angle to something less than 18° from the standpoint of the path length through the ionosphere, however, the resulting effective elevation angles would usually still be acceptably large from this point of view.

The whole process just described could be completed in about fifty days by causing the Geopause to advance by about 81°, instead of by 67° in each ten-day ground track interval. The Geopause elevation angles would then drop to less than 5°, which is much poorer from the standpoint of the ionospheric disadvantages. Or one could arrange to have Geopause advance by only about 58° in each ten-day ground track interval. This choice would diminish the ionospheric disadvantages, but not greatly. The survey would then take ten days longer to complete, and the angle between the two velocity components observed becomes smaller, which weakens the orthogonality property. The 67° advance may well turn out to be an optimum one. The final choice will probably depend largely upon the severity of the ionospheric problem which will be a function of the tracking system characteristics.

It has been estimated that a set of range-rate measures accurate to 0.03 millimeters per second obtained from a survey having this type of comprehensive coverage should provide the basis for determining the geoid to decimeter accuracy over the entire earth with a spatial resolution comparable to the gravity field satellite's altitude of about 250 to 300 kilometers. (24)

The radial component is the same as that which has been used to discover the lunar mascons and to map the lunar gravitational field in considerable detail. (33)

The along-track component has traditionally been the one which has provided much of the strength in existing solutions for geopotential coefficients.

This whole process could be carried out using a low-altitude spacecraft which would be in the same orbit as the one described but circling the earth in the direction opposite to that of the Geopause spacecraft. In such a case the ground tracks and hence, the gravitational regions sampled would be shorter, about 109 degrees instead of 134 degrees, and there would be correspondingly more of them in the ten-day interval, i.e., about 175 in each 159 revolutions instead of about 143. The smaller number of longer paths might be preferable, since they approach more closely the ideal of a single, continuous record.

2. Sea Surface Topography Surveys

It is planned to make observations of the distance from the spacecraft to the sea surface by means of satellite-borne altimeters. Initially, accuracies of several meters are expected. It is anticipated that it should be possible to improve the observational accuracy to the decimeter level in terms of the altimeter instrument and the interpretation of the measures in terms of mean sea level in the observed area, which is convenient to think of as the local mean sea level. Departures of the mean sea level surface from the geoid due to currents, deep ocean tides, storm surges, etc., are of the order of a meter or so. It was indicated in the above discussion that it appears that it will be possible to determine the position of the geoid relative to the center of the earth with an accuracy of the order of a decimeter. Radar measures of the distance from an altimeter spacecraft to the local mean sea level surface to decimeter accuracy can thus be used to make studies of the departures of the mean sea level from the geoid, provided we know the position of the altimeter satellite with decimeter accuracy relative to the geoid or to the center of the earth, say. Knowledge of the departures of the ocean surface from the geoid over the whole earth to decimeter accuracy will provide fundamental boundary condition information in connection with the problem of determining the general circulation of the oceans.

Up to now, attacks upon the problem of the general circulation involve the making of the assumption that at some depth, a kilometer or two, say, there is a level of no motion. It is considered that this assumption may be invalid, and that substantial errors may occur in the resulting models of the general circulation of the oceans. Here again the Geopause satellite system can provide a crucial link.

This problem can be attacked by placing the altimeter spacecraft in an orbit which lies in the Geopause orbit plane. The altimeter spacecraft will probably orbit at a height in the general neighborhood of some 700 kilometers.

In this case, use is made of two Geopause spacecraft following the same orbital path, but separated in mean anomaly by about ninety degrees. When the true anomaly of the low altitude spacecraft is between that of the two Geopause spacecraft, it can be tracked simultaneously by both of them. This portion of the low altitude spacecraft orbit can be thought of as being the prime coverage arc.

Range tracking of decimeter accuracy from the two Geopause spacecraft to the altimeter spacecraft in this prime coverage arc can give the two in-plane components of the position of the low altitude spacecraft relative to the Geopause spacecraft system. This set of Geopause spacecraft can thus become the defining elements of a coordinate system in space. From these two in-plane components of the altimeter spacecraft position relative to the Geopause satellite coordinate system it is possible to derive any other pair of in-plane components of the low altitude altimeter satellite's position including, for example, those in the radial and along-track directions. Since the radial position of the Geopause spacecraft is known relative to the earth's center with decimeter accuracy, one has then the radial position of the altimeter satellite relative to the earth's center with corresponding accuracy. This then provides the basis for the full exploitation of the decimeter satellite altimeter capability for a whole range of oceanographic studies which are important from both the scientific and applications standpoints.

The tracking of a low altitude altimeter spacecraft can be viewed not only in terms of Figure 3, but also in terms of the ground tracks of the three satellites as is indicated in Figure 5. We see there the ground tracks of the two Geopause spacecraft and the altimeter spacecraft during the prime coverage arc. Ground tracks for two successive revolutions of the low altitude spacecraft are seen in Figure 6. Again by choosing the commensurabilities of the Geopause and the altimeter spacecraft orbits properly, complete coverage of the earth can be had. The spacing of the altimeter orbit ground track may be different from that of the gravity field spacecraft. For example, seven-degree spacing appears to be of interest from certain standpoints for oceanographic studies. The method for building up complete coverage of the ground tracks of the altimeter spacecraft by means of sets of adjacent primary coverage arcs along the ground track is analogous to the one described earlier in connection with the coverage for the gravity field spacecraft. Here, with the ninety degree separation between the two Geopause spacecraft, the primary coverage arc is about 102° long. Thus a complete survey can be completed in four ground track coverage intervals instead of six, as in the case of the gravity field spacecraft for which the coverage arc of primary interest is about 67°. The ninety degree separation between the two Geopause spacecraft results in the path between the Geopause and altimeter spacecraft passing a little below the altimeter spacecraft orbit at the extremes of the primary coverage arc. The path is high enough, however, so that ionospheric effects are not unduly troublesome.

3. Meteorological Surveys

a. Atmospheric Surveys

The greatly improved knowledge of station locations derived from the tracking of the Geopause from the fundamental stations, and the correspondingly improved knowledge of the earth's gravitational field obtained from the tracking of the gravity field spacecraft and the Geopause spacecraft should improve the potential of a number of other experiments which depend upon the ability to determine orbits accurately. An example is the experiment proposed by Lusignan in which two spacecraft of the Nimbus type are positioned about a radian apart in the same orbit at about 1,000 kilometers altitude so that the ray path joining them passes through the atmosphere at altitudes of interest, e.g., at or above the 300 millibar level, say. (34) The change in the length of the path joining the two spacecraft due to atmospheric refraction furnishes a measure of the atmospheric density near the path's point of minimum height. (34) This change is to be found by comparing the observed range between the spacecraft, which is affected by atmospheric refraction, with the actual range which is determined from independent knowledge of the orbital positions of the two spacecraft. The experiment thus becomes, in effect, an experiment in the precise determination of the relative orbital positions of spacecraft in the 1,000 kilometer altitude range. This is an experiment, then, that will be greatly benefited by the results obtained from the Geopause and gravity field spacecraft. The atmospheric probing experiment could also be conducted by using two Geopause spacecraft travelling in the same orbital path but separated by almost 1/2 a revolution so that the path joining them passes through the atmosphere at the altitude of interest.

The advantage of this approach lies in the fact that the orbital positions and hence the geometrical distances between the two Geopause spacecraft should be known with greater accuracy than in the case of the lower altitude spacecraft in orbits of the Nimbus type. The disadvantage lies in the longer time required to conduct the sampling with a given resolution.

A third approach could involve the use of a pair of spacecraft in an orbit in the 700 to 1000 kilometer altitude range deployed in the manner proposed by Lusignan and tracked by two Geopause spacecraft in the way which was described above for the altimeter spacecraft.

b. Meteorological Photographic Surveys

The Geopause satellite also provides an ideal platform for conducting meteorological photographic surveys in the polar regions. Viewing of both the North and South poles can occur on a regular basis.

The Geopause satellite is in a good position for polar viewing, i.e., within about 50° to 55° of the pole, for about four hours during each revolution. During such a period, it would be possible to obtain a sequence of about a dozen synoptic photographs or images separated by 20 minute intervals. These sequences would be similar to the full-earth photographs obtainable from ATS & SMS. The Geopause photographs and images in the polar regions would provide a key complement to the ones from ATS & SMS which cover portions of the region around the equator between the latitudes of about 50 degrees.

As it continues around its orbit, the Geopause satellite can provide additional full-earth photographic coverage of most of the earth's surface in about one and a sixth days.

The Geopause satellite system also appears to have growth potential in connection with more advanced meteorological experiments such as those involving cloud and wind velocities, for example. Cloud velocities and, in appropriate circumstances, wind velocities, can be inferred from photographs taken about an hour apart. It appears that the four-hour Geopause polar observation interval is more than adequate for this purpose. It is of interest from certain standpoints to obtain such wind velocities once or twice a day. Here again the 14 hour Geopause orbit period is suitable.

Full-earth photographs of the polar regions obtained from Geopause would also be expected to be of interest in connection with studies of the dynamics of the polar ice cap and ice fields.

IV. A GEOPAUSE SPACECRAFT CONCEPT

A sketch of a possible configuration for the Geopause spacecraft is indicated in Figure 7 . The aspect sketched there indicates some of the desirable features, e.g., the spherical shape, the large antenna for the range and range-rate tracking of low altitude spacecraft, etc. It appears that versions with diameters in the range from two to three and a half meters or so could be accommodated in typical launch vehicles.

The upper half would be covered with solar cells and the lower half with a radome which would be nearly transparent to the radiation from the large parabolic antenna used for satellite-to-satellite tracking and other tracking purposes. The spacecraft would be earth-pointing and would probably be equipped with a control system employing reaction wheels. A nuclear power supply system might be used, thus making possible a smaller spherical design which would in turn diminish the effect of the radiation pressure perturbation uncertainty. More serious thermal problems would probably arise using such a design approach, however.

An accelerometer might be used to measure the total effect of the non-gravitational forces due to radiation pressure, earth-shine, neutral and charged particle drag, micro-meteorites, etc. These effects might also be handled by means of a drag-free or surface force compensation system. The satellite-to-satellite tracking antenna beam might be pointed by means of a feed system employing a phased array technique. A laser corner reflector system, consisting perhaps of a single decimeter cube, could be mounted below the antenna feed. A version of the Geopause could also include a space-borne laser. Such possibilities for a Geopause spacecraft concept are in the thinking stage at the moment. It is anticipated that firmer ideas will be worked out through further study.

Analyses of the properties of the Geopause spacecraft are continuing in order to provide more detailed estimates of its properties in connection with the various applications sketched here. Results obtained to date are, however, encouraging. Geopause offers the promise of making noteworthy contributions in a number of areas relating to orbit determination, geodesy, and earth physics including earth dynamics and oceanography.

It is a pleasure to express appreciation to C. A. Wagner and J. G. Marsh for discussions and assistance in connection with computing relating to gravitational perturbations of satellites at large distances and tracking station locations.

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EARTH PHYSICS PROGRAM GOALS

~10m ⟶ ~0.1m FOR: EARTH DYNAMICS | FIELDS | OCEAN DYNAMICS

~10m	~0.1m FOR:	EARTH DYNAMICS	FIELDS	OCEAN DYNAMICS
STATE OF ORBIT ANALYSIS ART NOW	RANGE TRACKING PRECISION BY 1973	EARTHQUAKE STUDIES FAULT MOTIONS POLAR MOTIONS ROTATION RATES SOLID EARTH TIDES	GRAVITY GEOID MAGNETIC	OCEAN TOPOGRAPHY GENERAL CIRCULATION & CURRENTS MASS & HEAT FLOW TIDES, TSUNAMIS STORM SURGES

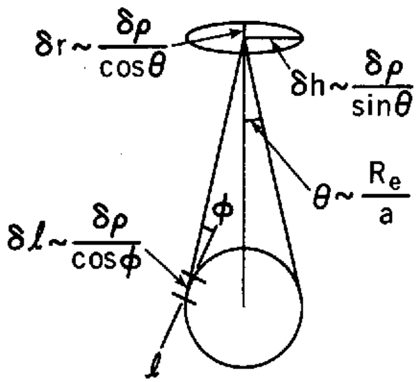
PROBLEM AREAS

ORBIT DETERMINATION — TRACKER BIASES — ENVIRONMENT GRAVITY FIELD — STATION POSITIONS

GEOPAUSE APPROACHES

GEOPAUSE ORBIT:

PERIOD ~ 14^h, a ~ 4.6 e.r., NEARLY CIRCULAR, POLAR, NORMAL TO ECLIPTIC

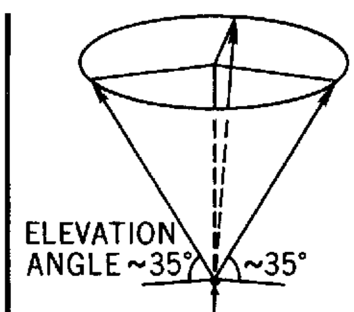


ACCURACIES OF ORBIT RADIUS AND LINE OF SIGHT COORDINATES ARE CLOSE TO RANGE TRACKING ACCURACIES

TRACKER BIASES DETERMINED BY MEANS OF CONTINUAL REDUNDANT DATA

ORBIT	5 cm GRAVITY ERROR TERMS
GEOS	~1000
GEOPAUSE	~6

THUS AT THE GEOPOTENTIAL BOUNDARY i.e., THE GEOPAUSE REMAINING ENVIRONMENT QUANTITIES FROM ORBIT ANALYSIS & ACCELEROMETERS

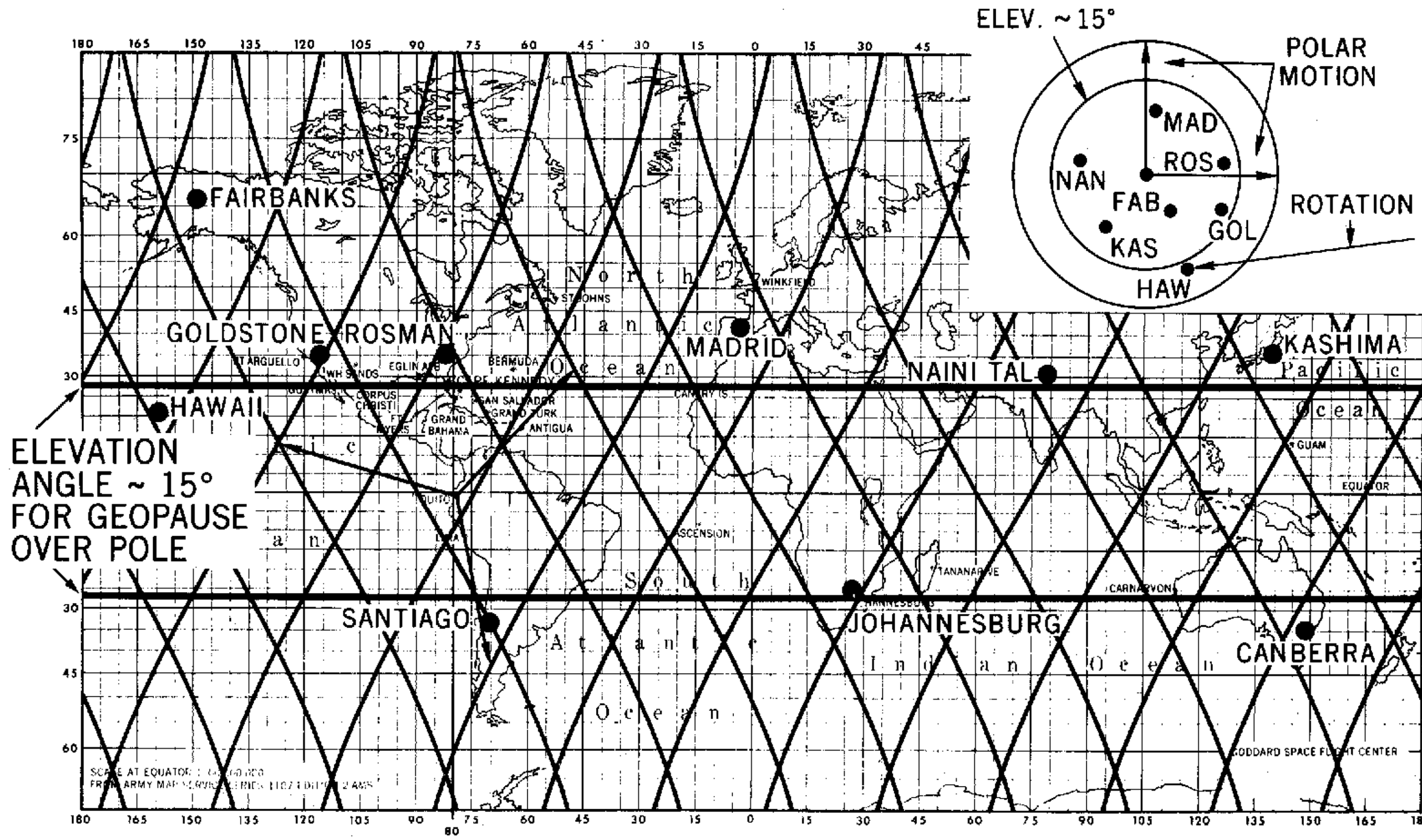


STATION AZIMUTHS 120° APART

ORBIT YIELDS ORTHOGONAL GEOMETRY FOR STATION POSITIONING

Figure 1

GEOPAUSE ORBIT YIELDS THE GEOMETRY FOR DETERMINATION OF ORBIT, TRACKER BIASES, GM, STATION LOCATIONS, FAULT MOTIONS, POLAR MOTIONS, ROTATION RATES, TIDES



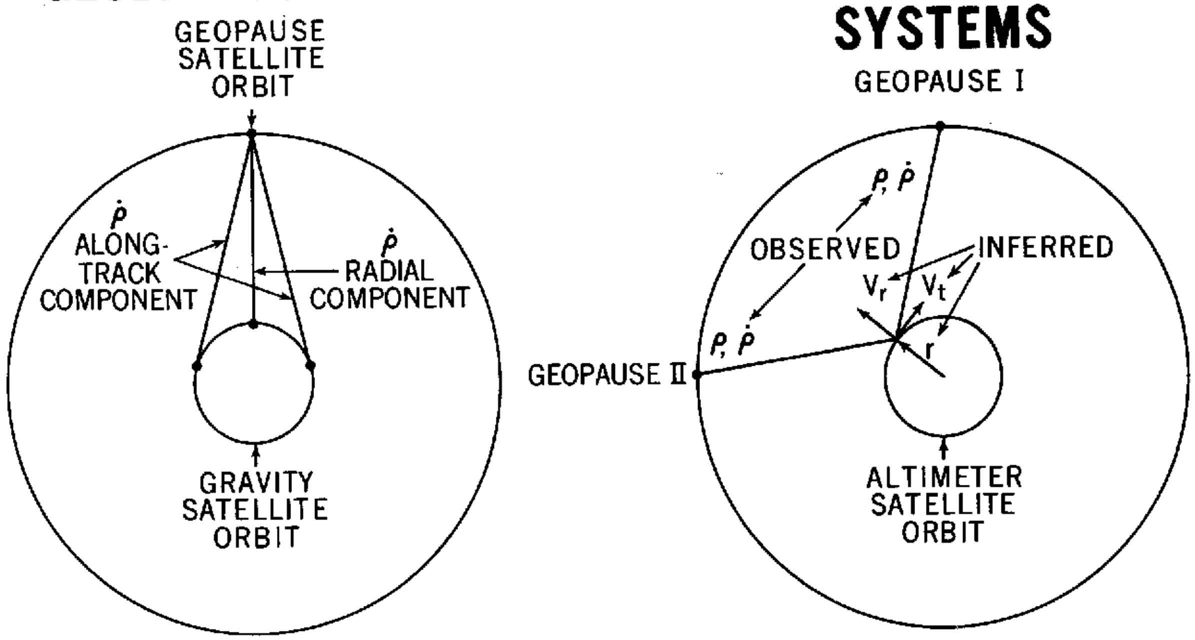
GEOPAUSE SUBSATELLITE TRACKS DURING ONE WEEK

● TYPICAL FUNDAMENTAL STATIONS

GEOPAUSE WITH 2cm RANGE TRACKING DATA YIELDS DECIMETER STATION LOCATIONS AND FAULT MOTIONS

Figure 2

GEOPAUSE FOR
GLOBAL SURVEYS AND REFERENCE COORDINATE SYSTEMS



GEOPAUSE TRACKING COPLANAR
DRAG-FREE GRAVITY SATELLITE
TO 0.03 mm/sec YIELDS
DECIMETER GEOID
WITH 2.5° RESOLUTION
IN 2 MONTHS

2 GEOPAUSE SATELLITES & COPLANAR
ALTIMETER SATELLITE YIELD
OCEAN SURFACE HEIGHT ABOVE GEOID
WITH 7° RESOLUTION
IN 2 WEEKS

OCEAN SURFACE

TIDES, TSUNAMIS, STORM SURGES ⟵ ⟶ CURRENTS, GENERAL CIRCULATION &

GEOID

BOUNDARY CONDITIONS FOR MASS & HEAT FLOW

Figure 3

GEOPAUSE AND EARTH HARMONIC SUBSATELLITE TRACKS IN A 40 MINUTE INTERVAL

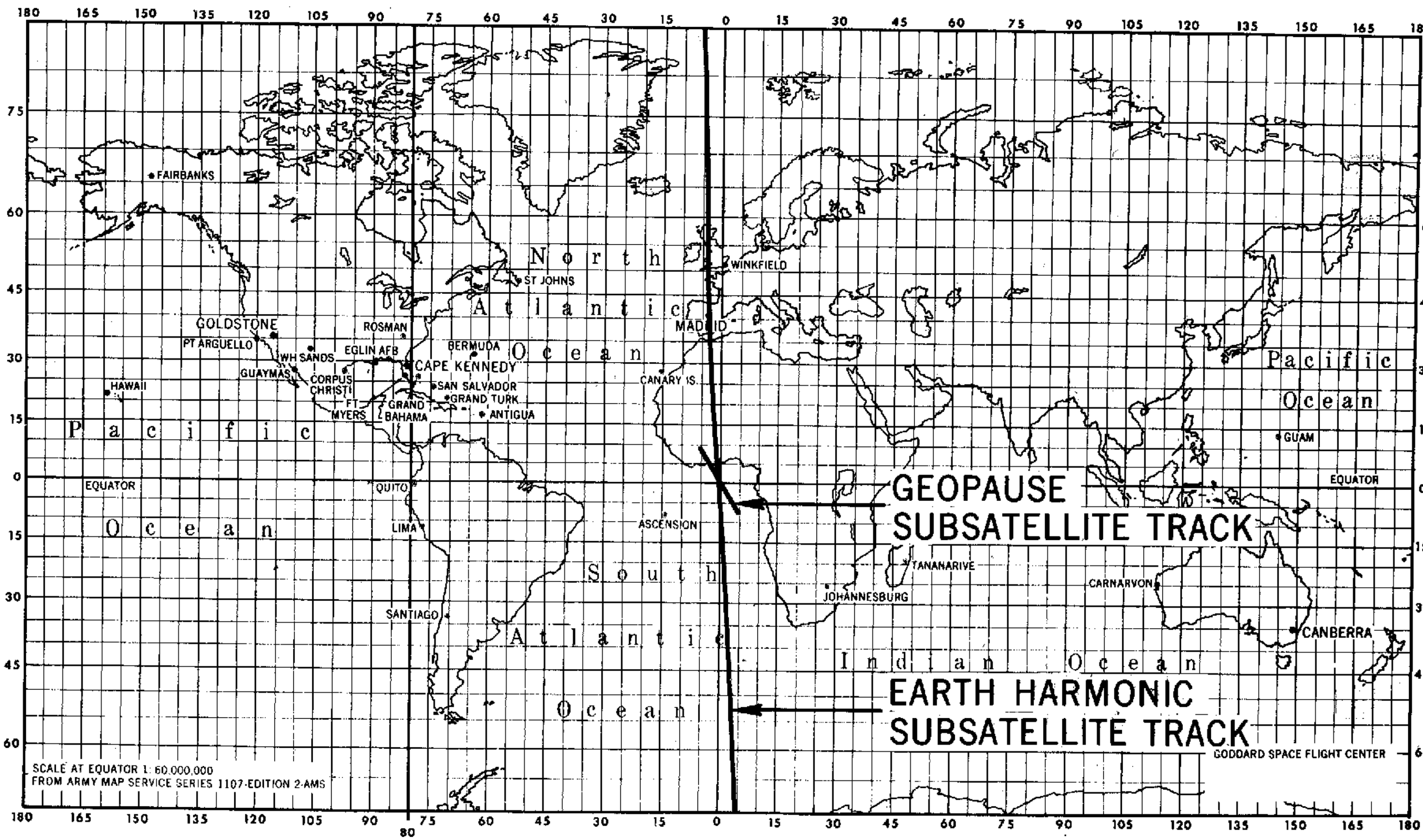


Figure 4

SUBSATELLITE TRACKS OF 2 GEOPAUSE SATELLITES AND AN ALTIMETER SPACECRAFT IN A 25 MINUTE INTERVAL

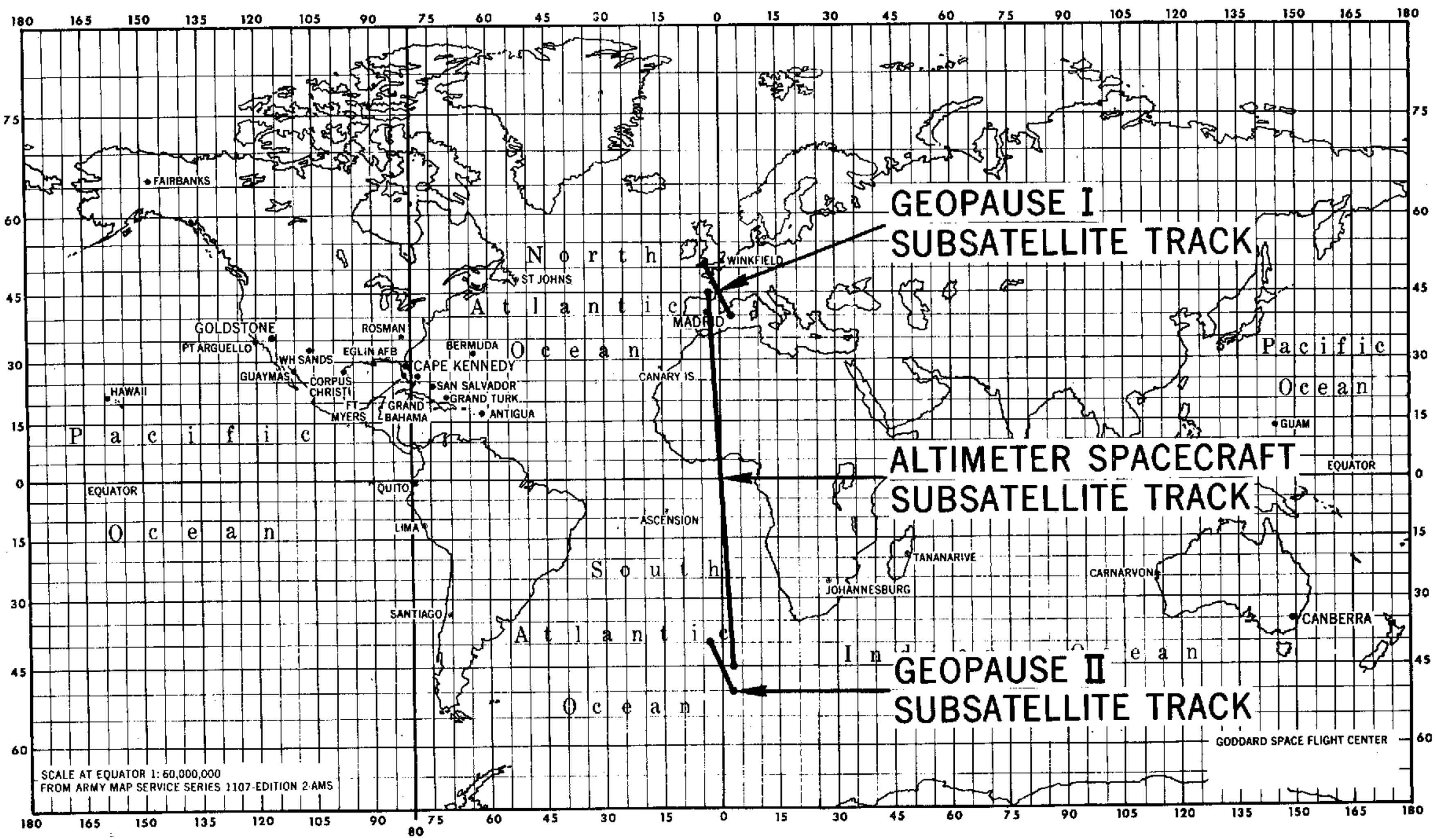


Figure 5

SUBSATELLITE TRACKS DURING PRIMARY COVERAGE INTERVALS FOR SATELLITE-TO-SATELLITE TRACKING BETWEEN 2 GEOPAUSE SPACECRAFT AND AN EARTH HARMONIC SPACECRAFT IN 2 SUCCESSIVE REVOLUTIONS OF THE EARTH HARMONIC SPACECRAFT

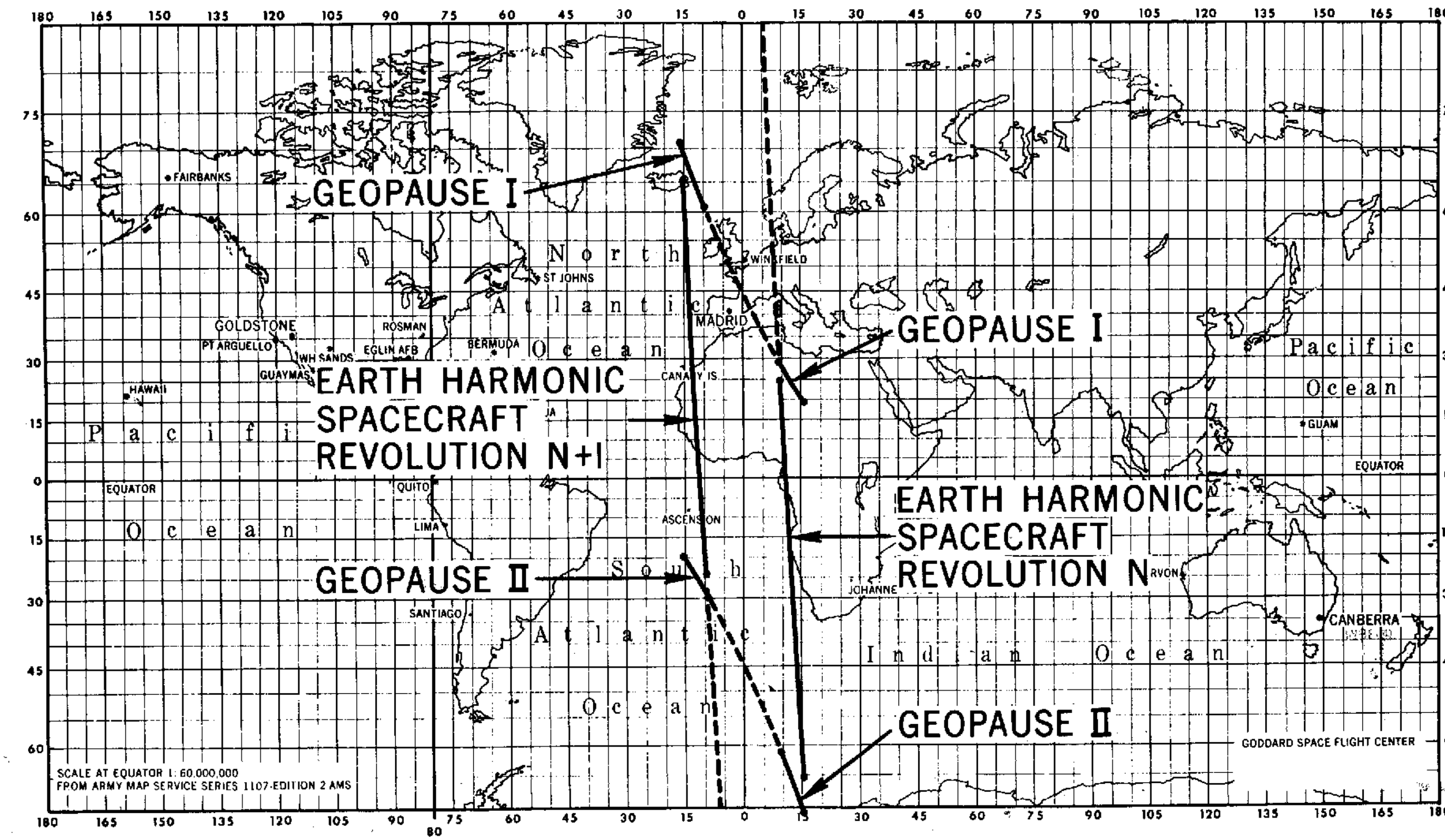


Figure 6

GEOPAUSE SPACECRAFT CONCEPT

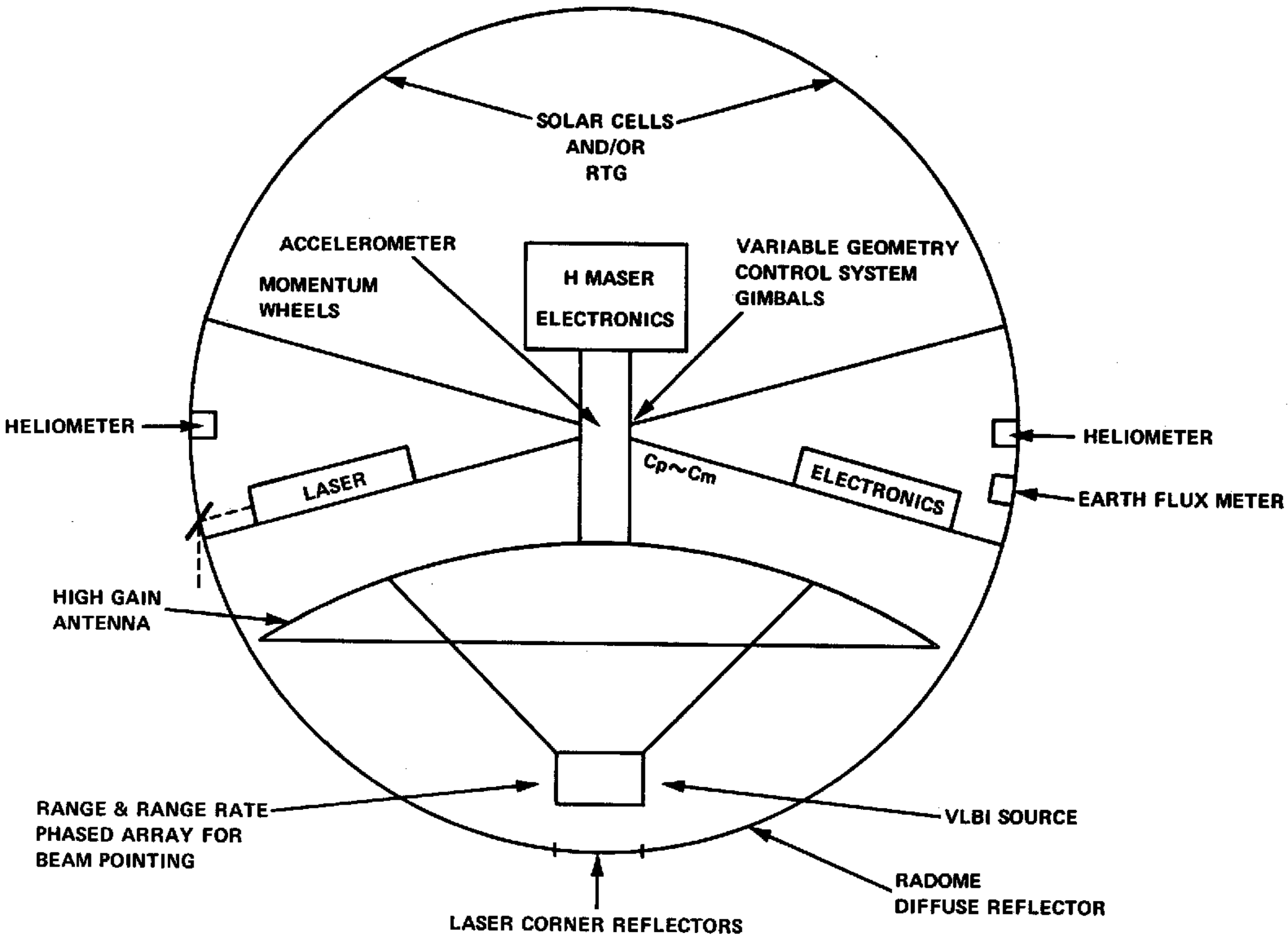


Figure 7

Table I

General Determinations of Geopotential Coefficients

Author or Designation	Year	Reference Number	Basis			Field Characteristics	
			Satellite Data		Other Information		
			Number of Satellites	Tracking Systems		Last term in Complete Portion	Number of Coefficients
1. NWL 5E-6	1965	1	3	Doppler		7, 6	64
2. APL 3.5	1965	2	5	Doppler		8, 8	84
3. SAO M-1	1966	3	16	Optical		8, 8	122
4. Kaula K-8	1966	4	12	Optical, Doppler		7, 5	99
5. Kaula C	1966	4			Determinations 1-4	7, 2	
6. Rapp	1967	5	16	Optical	Gravimetry	14, 14	219
7. Köhnlein	1967	6	16	Optical	Gravimetry	15, 15	250
8. Kaula UCLA	1967	7	9	Optical, Doppler	Gravimetry	8, 8	
9. Rapp	1968	8	16	Optical	Gravimetry	14, 14	
10. SAO COSPAR	1969	9	24	Optical, Range, Range Rate		14, 14	280
11. SAO B6.1	1969	10	24	Optical, Range, Range Rate		16, 16	
12. SAO B 13.1	1969	11	24	Optical, Range, Range Rate	Gravimetry	16, 16	314
13. SAO SF	1969	12	24	Optical, Range, Range Rate	Gravimetry	16, 16	316
14. GSFC 1.70 C	1970	13			Determinations 1-9, 11, 12	15, 15	249
15. SAO 69 (II)	1970	14	21	Optical, Range, Range Rate	Gravimetry	16, 16	316

Table II

Resonance Determinations of Geopotential Coefficients

Author or Designation	Year	Reference Number	Basis		Field Characteristics
			Numbers and Types Satellites	Reference Coefficients	Coefficients Determined
1. Wagner	1967	15	3 24-hour		(2,2), (3,1), (3,3)
2. Gaposchkin and Veis	1967	16	3 12th order	SAO M-1	(13,12), (14,12), (15,12)
3. Murphy and Victor	1967	17	2 12-hour		(2,2), (4,4)
4. Yionoulis	1968	18	3 13th order		(13,13), (15,13), (17,13)
5. Wagner	1968	19	2 12-hour		(3,2), (4,4)
6. Murphy and Cole	1968	20	1 12th order		(14,12), (15,12)
7. Wagner	1968	21	3 24-hour 2 12-hour		(2,2), (3,1), (3,2) (3,3), (4,4)
8. Douglas and Marsh	1969	22	1 13th Order	Yionoulis, 1968	(14,13)
9. Wagner	1969	23	4 24-hour 4 12-hour	SAO B13.1	(2,2), (3,2), (3,3), (4,4)

TABLE III

ℓ	$\Delta\ell_{1,2}$	$\Delta\ell_{2,3}$	$\Delta\ell_{1,3}$	$\sigma_3 \times 10^8$
2	2.1	0.25	2.4	0.6
3	18.0	9.9	10.2	1.0
4	8.2	7.4	5.3	0.7
5	11.9	11.8	4.1	1.5
6	14.8	13.3	7.1	
7	12.7	12.2	7.2	
8			5.3	

$$\Delta\ell_{i,j} = \frac{10^8}{2m} \sum_{k=1}^{m} \left\{ \left[C_{\ell k,i} - C_{\ell k,j} \right] + \left[S_{\ell k,i} - S_{\ell k,j} \right] \right\}$$

1 = SAO M-1

2 = Mean of NWL 5 E-6 and APL 3.5

3 = SAO 69 (II)

Table IV
Satellite Position Differences Associated with Various Gravity Models

SAO M-1 (modified*) vs.	Position (meters)							
	GEOS I				GEOS II			
	Radial	Cross Track	Along Track	Total	Radial	Cross Track	Along Track	Total
SAO M-1 (unmodified)	30.0	17.1	286.4	288.5	22.3	10.3	232.2	234.2
SAO COSPAR (no. 11th)	8.9	12.8	29.5	33.4	24.7	18.2	92.8	97.8
SAO 1969	8.3	13.5	26.9	31.2	16.6	19.3	59.2	64.4
Köhnlein	16.4	16.1	213.0	214.2	20.1	16.9	129.1	131.7
Köhnlein (modified)	9.2	10.9	28.0	31.4	11.8	15.1	41.9	46.1
Rapp	48.3	29.5	129.4	141.2	38.8	37.7	157.6	166.6
Rapp (modified)	46.4	33.2	99.9	115.0	36.2	39.1	84.8	100.1
APL 3.5	46.1	46.8	175.7	187.1	71.8	55.2	674.3	680.4
APL 3.5 (modified)	42.5	41.6	90.1	107.9	34.7	45.4	88.1	105.2
NWL 5E-6	16.3	16.6	204.0	205.3	46.4	80.9	374.6	386.1
NWL 5E-6 (modified)	16.7	12.9	49.1	53.4	26.3	80.0	82.9	118.2
Kaula	32.5	42.2	114.1	125.9	47.6	43.5	232.8	241.4
Kaula (modified)	32.1	42.5	110.2	122.4	48.7	42.0	140.5	154.6

*Gaposchkin & Veis (1967) 12th order terms for GEOS-I and Ylonoulis (1968) and Douglas & Marsh (1968) 13th order terms for GEOS-II.

TABLE V

GEOPAUSE SATELLITE ORBIT PROPERTIES
SMALL GRAVITY PERTURBATION UNCERTAINTIES

	l	m	p	q	UNCERTAINTIES IN CM. R, RADIAL COMPONENT (> 5 CM)	T, TRANSVERSE COMPONENT	$\frac{T}{a}$ (> 5 CM)
RESONANT PERTURBATIONS	2	2	0	-1	6		
	2	2	1	1	33	45	10
	3	2	1	0	13	170	37
NON-RESONANT PERTURBATIONS	2	2	0	0	8		
	3	3	1	1	14		

$a = 4.578$, $e = 0.001$, $i = 89^{o}$

GEOPOTENTIAL COEFFICIENT UNCERTAINTY ASSUMPTIONS:

$l = 2$: 2.5×10^{-8}

$l > 2$: 5×10^{-8}

TABLE VI

GEOPAUSE SATELLITE ORBIT PROPERTIES

DETERMINATION OF COORDINATES FOR STATIONS OF A TYPICAL FUNDAMENTAL NETWORK

ADJUSTED PARAMETER	STANDARD DEVIATION
GM	3.896E-09
C(2.2)	3.761E-09
S(2.2)	2.560E-09
ROSMAN X	12
ROSMAN Y	33
ROSMAN Z	20
SNTAGO X	39
SNTAGO Y	40
SNTAGO Z	14
ROSMAP Y	39
ROSMAP Z	21
MOJAVE X	34
MOJAVE Y	34
MOJAVE Z	23
MADRID X	27
MADRID Y	14
MADRID Z	32
JOBURG X	49
JOBURG Y	16
JOBURG Z	23
TOKYO X	24
TOKYO Y	22
TOKYO Z	15
ORRORL X	36
ORRORL Y	25
ORRORL Z	40
ULASKR X	17
ULASKR Y	12
ULASKR Z	30
HAWAII X	30
HAWAII Y	21
HAWAII Z	19

ASSUMPTIONS: RANGE BIAS, 10 CM. RANGE RATE BIAS, 0.05 MM/S, GEOPOTENTIAL HARMONIC COEFFICIENT UNCERTAINTIES = 0,25 (SAOMI-APL 3.5) TRACKING INTERVAL 1 WEEK. LONGITUDE COORDINATE OF ROSMAP UNCERTAINTY, 1 MM. STANDARD DEVIATIONS OF COORDINATES SHOWN IN CENTIMETERS. THE RMS VALUE OF THE STATION COORDINATE UNCERTAINTIES IS 28 CM.